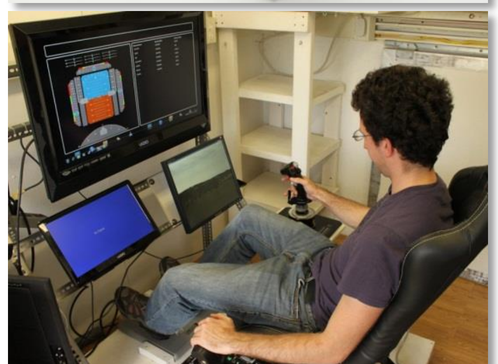
NASA LEARN Program

Cooperative Gust Sensing and Suppression for Aircraft Formation Flight






Grant Number: NNX13AB74A

Flight Control Systems Lab (FCSL), Interactive Robotics Lab (IRL)
Department of Mechanical and Aerospace Engineering,
West Virginia University (WVU)

Outline

I. **Project Overview & Status**

II. Formation Flight Simulator

III. Experimental Flight Validation

IV. Gust/Wake Sensing and Suppression Control

V. Conclusions & Plan for Future Research

Objectives & Challenges

NASA LEARN Project Phase I:

“Cooperative Gust Sensing & Suppression for Aircraft Formation Flight”

PI: Dr. Marcello Napolitano, Co-PI: Dr. Yu Gu *(West Virginia Univ.)*
Co-PI: Dr. Haiyang Chao *(currently at University of Kansas)*

Objectives

Development of a cooperative strategy for gust sensing and suppression within a formation flight.

Tasks

1. Cooperative Gust and Turbulence Sensing and Prediction;
2. Flight Simulation and Validation;
3. Active Gust Suppression Control.

Project Introduction

Innovation:

1. Use of a formation flying sub-scale aircraft for wind/wake sensing and estimation;
2. A cooperative gust/wake estimation and suppression control strategy that uses the leader aircraft as a remote wind sensor.

Impact:

1. Enabling the technology for routine formation flight (toward environmentally responsible aviation operations);
2. Similar gust sensing and suppression control algorithms could be introduced on commercial aircraft with the goals of reducing gust load and increasing passenger comfort;
3. Providing experimental validation of wake models.

Project Status

Videos of the WVU close formation flight experiments available at:

https://www.youtube.com/watch?v=3tKVDRj0UYw

https://www.youtube.com/watch?v=LssOqx9knIY

Deliverables to date

1. **Gust estimation method from onboard sensor measurements;**
   - Conference paper presented at the 2013 AIAA GNC Conf.
   - Conference paper submitted to the 2014 ACC (details in next page).
2. **Preliminary set of active gust suppression control laws;**
   - Preparation for a conference submission to AIAA GNC 2015.
3. **Comprehensive formation flight simulator;**
   - Conference paper submitted to ACC 2014.
4. **Multi-UAV framework including both hardware and software to support further application of formation flight test;**
   - Conference paper submitted to ACC 2014.
5. **Project website: http://www2.statler.wvu.edu/~irl/page16.html**

Publications

1. Matthew Rhudy, Mario L. Fravolini, Yu Gu, Marcello R. Napolitano, Srikanth Gururajan, and Haiyang Chao, "*Cross-Platform Evaluation of UKF Airspeed Estimation using UAV Flight Data*", submitted to IEEE Transactions on Aerospace and Electronic Systems, currently under review.
2. Matthew Rhudy, Trenton Larrabee, Haiyang Chao, Yu Gu, and Marcello R. Napolitano, "*UAV Attitude, Heading, and Wind Estimation Using GPS/INS and an Air Data System*", AIAA Guidance, Navigation, and Control Conference, August, 2013.
3. Trenton Larrabee, Haiyang Chao, Yu Gu, and Marcello R. Napolitano, "*Wind field and wake estimation in UAV formation flight*", submitted to the 2014 American Control Conference, currently under review.
4. Caleb Rice, Yu Gu, Haiyang Chao, Trenton Larrabee, Srik Gururajan, and Marcello R. Napolitano, "*Control performance analysis for autonomous close formation flight experiments*", submitted to the 2014 American Control Conference, currently under review.

Project Personnel

Faculty Members

PI: Dr. Marcello Napolitano, WVU Professor.

Co-PI: Dr. Haiyang Chao, WVU Post-Doc (Jan. – July 2013), Assistant Professor at KU (Aug.2013 - present).

Co-PI: Dr. Yu Gu, WVU Assistant Professor

Students

- Trenton Larabee, M.S. Student (Task: gust and wake sensing algorithm design, simulation, and flight testing);
- Caleb Rice, M.S. Student (Task: formation flight controller implementation, simulation, and flight testing);
- Lucas Behrens, UG Senior (Task: UAV maintenance, and support of flight testing activities).

Technical Approach

Formation Flight

1. Design of outer loop flight controller (GPS Trajectory tracking);
2. Design of formation flight controller;

Gust & Wake Sensing

1. Gust sensing algorithm design;
2. Cooperative Gust/Wake sensing algorithm design;

Gust Alleviation Control

1. Design of gust suppression controller;
2. Simulation using “Phastball” mathematical model.

Flight Test Validation

1. Formation flight of two WVU “Phastball” aircraft;
2. Gust/wake sensing with different offsets for formation flight.

Outline

I. Project Overview & Status

II. Formation Flight Simulator

III. Experimental Flight Validation

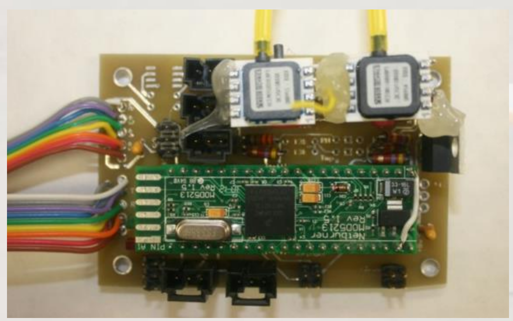
IV. Gust/Wake Sensing and Suppression

V. Conclusions & Plans for Future Research

WVU "Phastball" Sub-Scale Research Aircraft

Specifications	
Length	~ 88 in. (~2.2m)
Wing Span	~ 96 in. (~2.4m)
Take-off Weight	~ 26 lbs. (~12 Kg)
Max Payload	~ 7 lbs. (~3.2 Kg)
Thrust (Ducted Fan)	2 × 25 N
Flight Duration	~ 7 min.
Cruise Speed	~ 30 m/s
Controls	Elev., Ail., Rud., Throttle

WVU Gen-V Avionics



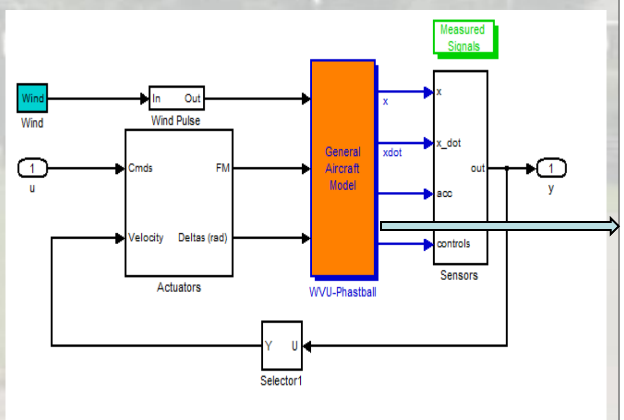
Key Features

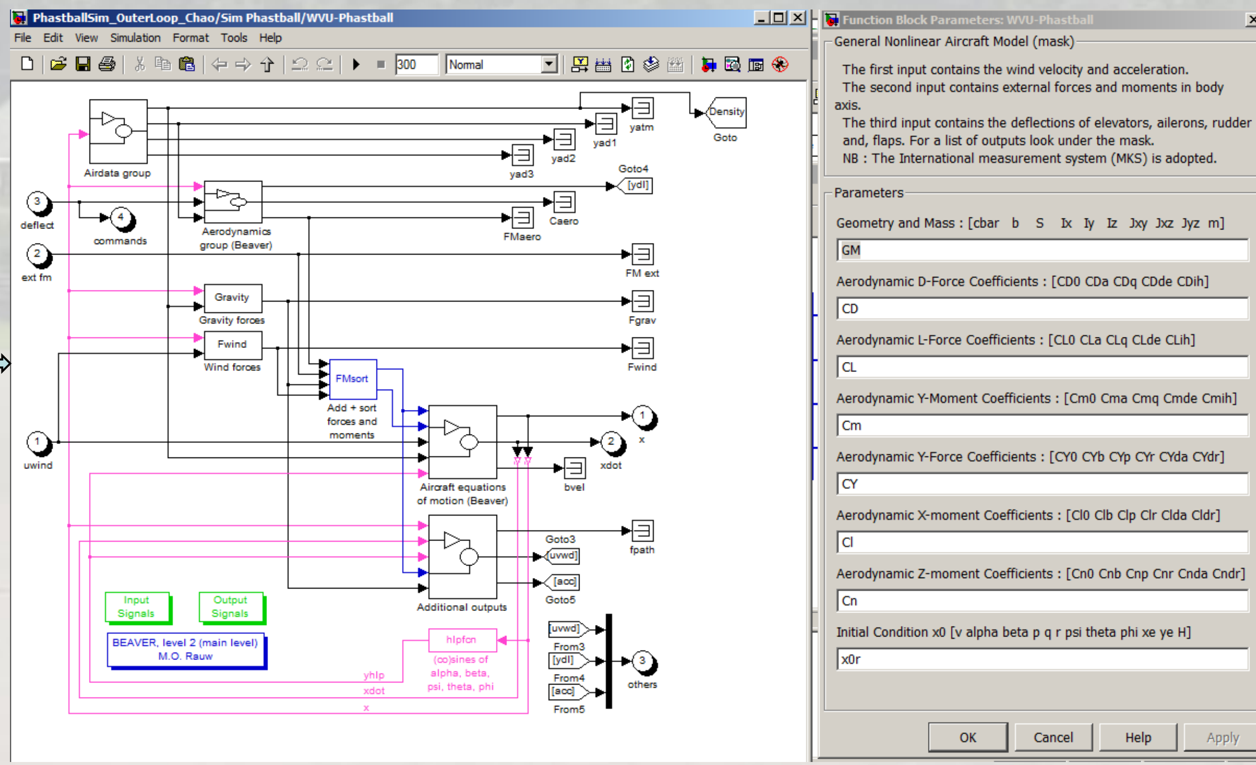
- **9 Controllable Channels**
- **GPS/IMU/MAG**
- **8ch. PWM Pilot Input**
- **12ch., 16-bit Aux A/D**
- **“Black-Box” Recorder**
- **RF Modem Up/Downlink**
- **400m Laser Range Finder**
- **Alpha/Beta Vanes**
- **Pitot-Tube for Static/Dynamic Pressure**
- **Humidity and Temperature**

"Phastball" Simulator (cont.)

- **WVU Simulink-based "Phastball" simulator (using FDC package)**

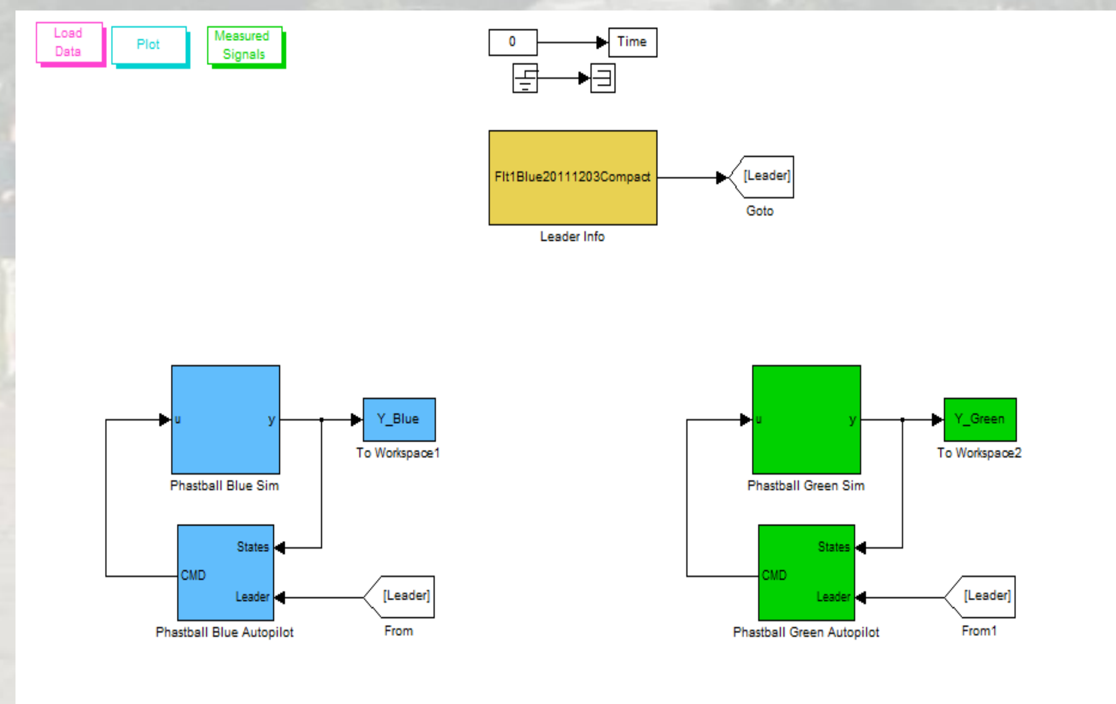
  (FDC model is modified based on PID-derived aerodynamic coefficients)

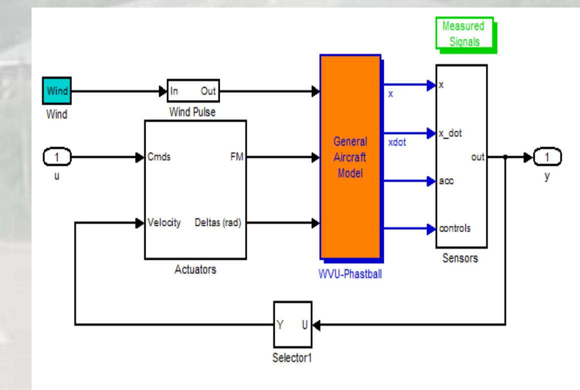


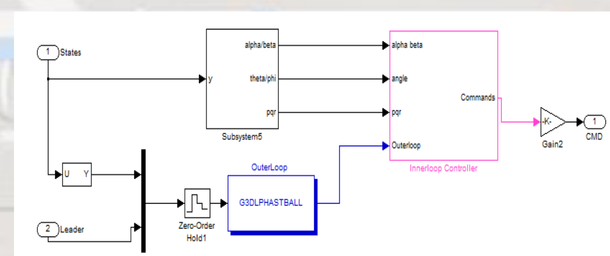


Formation Flight Simulator

- **WVU "Phastball" Formation Flight Simulator with 3-aircraft Formation**
  - Outer loop:
    - Vertical controller: based on PD type controller.
    - Horizontal controller: based on Non Linear Dynamic Inversion (NLDI)
  - Inner loop (attitude tracking): based on longitudinal/lateral LQ design



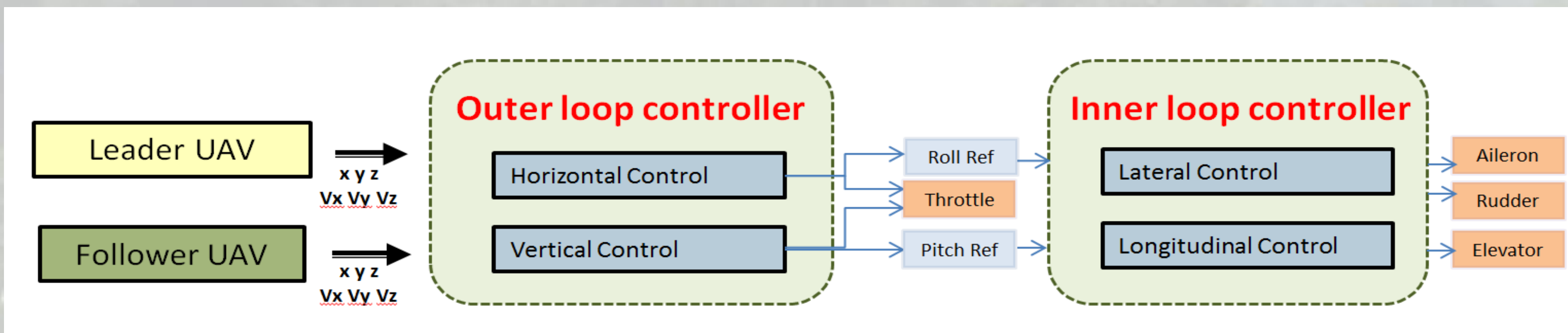


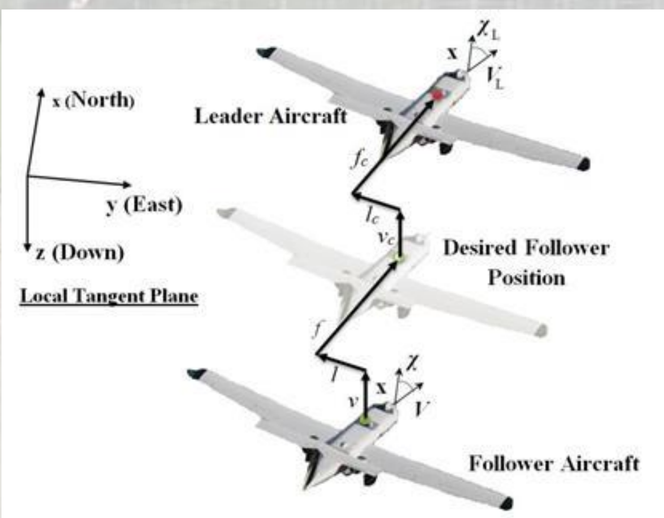


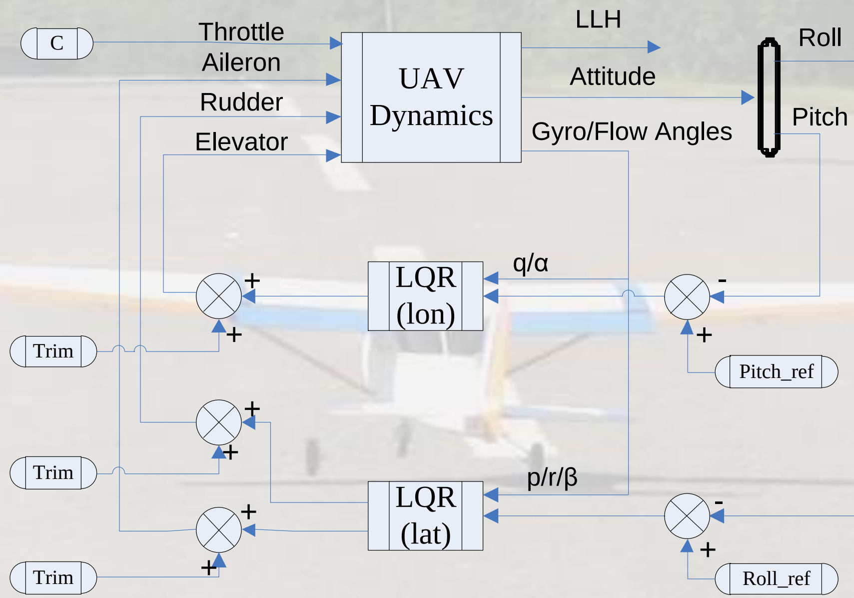
Autonomous Formation Flight – Design and Experiments, Y. Gu, G. Campa, M. Napolitano, et. al., InTech, Chapter 2009.

Formation Flight Controller

Overview of NLDI based Formation Flight Controller

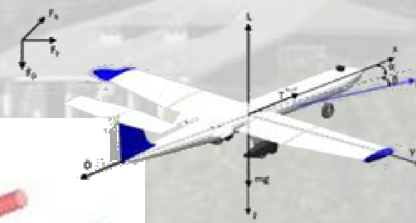


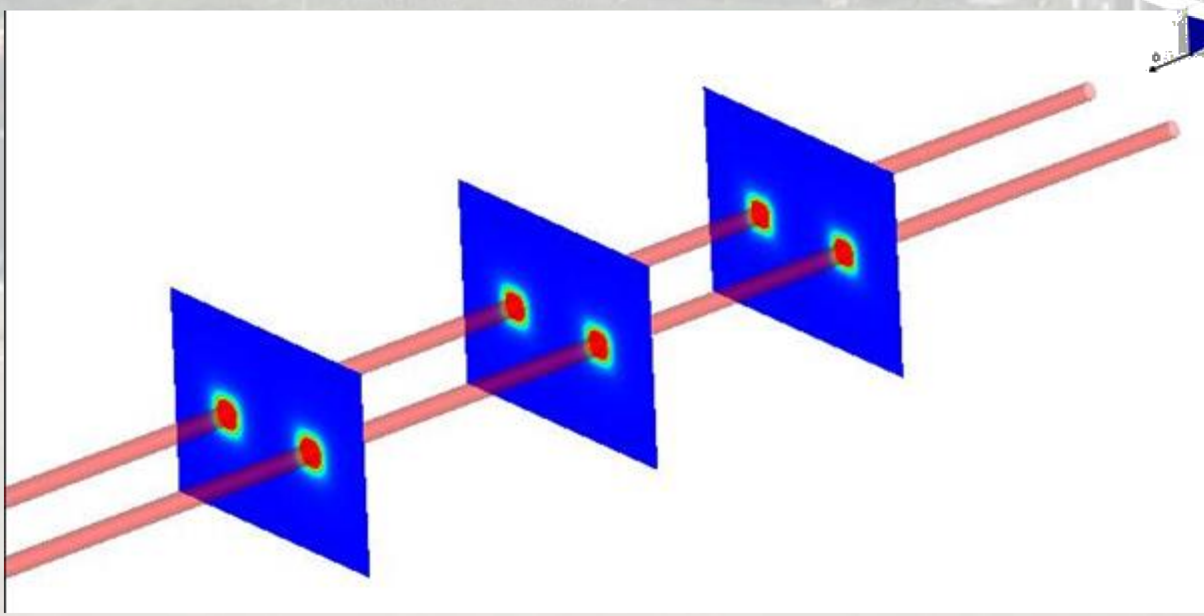




Wake Modeling and Simulation

- Hallock-Burnham vortex: $v_\theta(r) = \frac{\Gamma_i}{2\pi r}\frac{r^2}{r^2+{r_c}^2}$
- Sarpkaya wake delay model: $\Gamma_i = \Gamma_0 \exp\left(\frac{-Cd(\varepsilon\Gamma_0)^{0.25}}{1.2727 V_0 b_0}\right)$

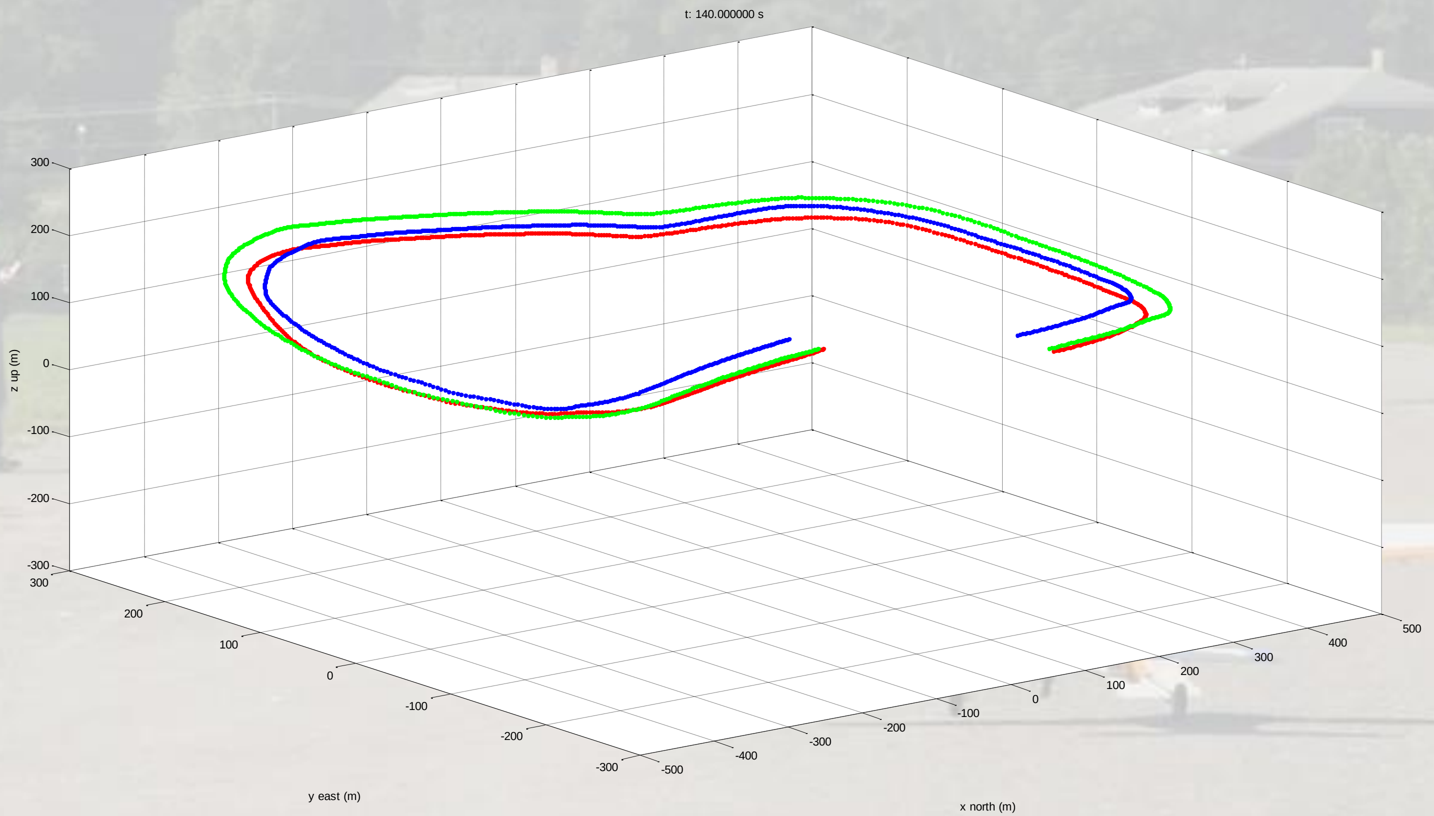




Wake vortices of Phastball UAV after roll-up (Core radius: 0.09 m, initial circulation: 1.72 m2/s)

Formation Flight Using “Phastball” Model (cont.)

- **Three Aircraft Formation Simulation**
  - Using RC flight data as the leader aircraft (Red).
  - Simulating followers (Blue/Green – 20/20/20 m).



Outline

WVU Formation Flight Test Objective

Flight Testing Plans

1) Validation of hardware system and formation flight control laws.
2) Wake visualization with a single aircraft.
3) Flight data collection for wind/gust/wake sensing with "Phastball" formation flight.

Milestones

1) Outer-loop controller validation flight (Virtual Leader).
   - Achieved on 07/22/2013;
2) Close formation flight of two "Phastball" aircraft (Leader-Follower).
   - Achieved on 09/08/2013;
3) Gust/wake measurements in close formation flight.
   - Achieved on 10/12/2013;

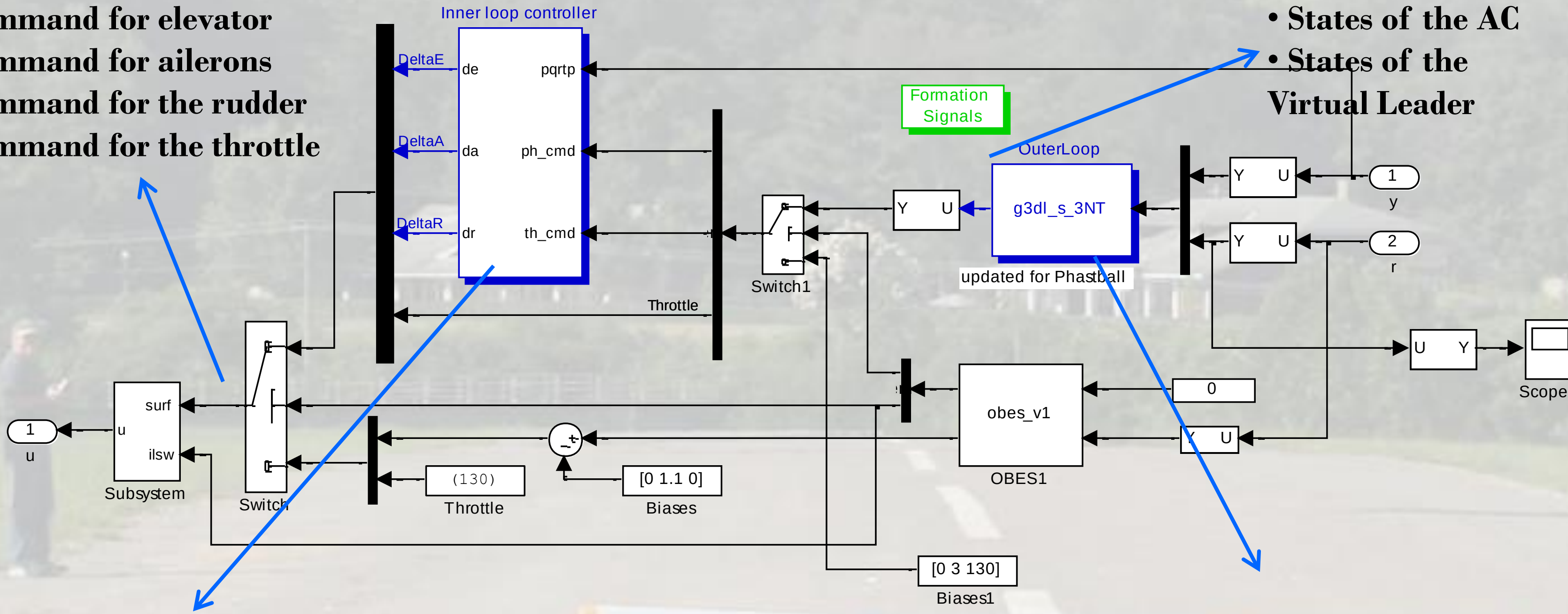
Formation Flight: Control Laws Implementation

Surface Deflections

- 1 command for elevator
- 1 command for ailerons
- 1 command for the rudder
- 1 command for the throttle

Inputs

- States of the AC
- States of the Virtual Leader



Inner Loop Controller

- generates $\delta_{el}, \delta_{al}, \delta_R$ to track θ_{ref}, ϕ_{ref}
- inputs: $[\alpha \quad \beta \quad p \quad q \quad r \quad \theta \quad \phi]$
- baseline design with LQ control techniques

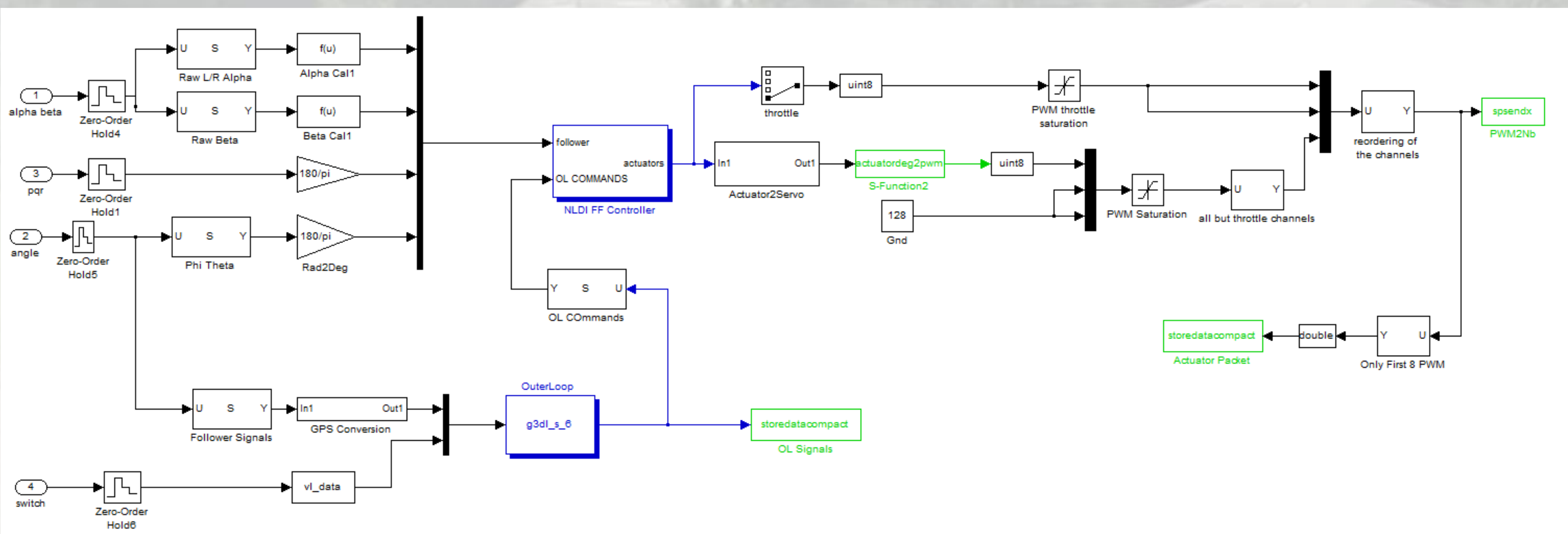
Outer Loop Controller

- generates θ_{ref}, ϕ_{ref} to track the virtual leader
- inputs: the states of the plane and the position of the VL
- based on NLDI control techniques

Formation Flight Control Scheme

Avionics Software

- Matlab/Simulink tool chain for flight avionics software downloading.
- Matlab/Simulink RTAI → C source files → Linux compilation → Executable



2013 Flight Season Summary

Flight Testing Session #	Date	Aircraft	Data Set #	Mission	Comments
1	5/25/2013	Blue	1	Trim/ Innerloop	tracking 0˚ roll and 2˚pitch
			2	Smoke	Plane was manually flown through a smoke screen for visualization of wing vortices
			3	Outer Loop	
		Green	1	Trim/ Innerloop	repeat of blue1 flight, rudder oscillations, taped on camera, one choke on reciever wire
2	6/14/2013	Green	1	Inner Loop	Favorable behavior seen during control activation
		Blue	1	OuterLoop	Catastrophic Failure resulting in crash.
3	7/12/2013	Green	1	Innerloop / background Online VL	Favorable behavior seen during control activation
			2	Online VL outerloop FF control	Forward distance appears to be negative when it should be positive.
		Red	1	Trim/ return to action	Red put back into action after losing Blue.
4	7/22/2013	Green	1	inner loop	Control on during straight legs
			2	outer loop	No unexpected errors. Clearance [10 0 0]
			3	outer loop	Vrt. Dist. Gain increased to 1.3
			4	outer loop	Successful virtual leader flight.
		Red	1	shake down	
			2	shake down	
5	7/25/2013	Green/Red	1	inner loop	Favorable behavior seen during control activation
			2	red downlink	green was recieving data while sitting on the ground and red flew
			3	Formation Flight!	red leader; green follower; Holding pattern ; Constant clearance
			4	Formation Flight!	Constant clearance
			5	Formation Flight!	Constant clearance
6	9/8/2013	Green/Red	1	Formation Flight!	Varying clearance
			2	Formation Flight!	Constant clearance
			3	Formation Flight!	Varying clearance
7	10/12/2013	Green/Red	1	Formation Flight!	Constant clearance
			2	Formation Flight!	Constant clearance
			3	Formation Flight!	Varying clearance
			4	Formation Flight!	Constant clearance

2-Aircraft Formation Flight Experiments Summary

Flight #	Mission	Description
1	Formation Flight, Holding Pattern	Forward Clearance: 50m
2	Formation Flight, Holding Pattern	Forward Clearance: 40m
3	Formation Flight, Holding Pattern	Forward Clearance: 30m
4	Close Formation Flight with Pilot Adjustments	Varying Clearance: Forward 24±12m, Lateral ±12m, Vertical ±12m
5	Close Formation Flight, Holding Pattern	Forward Clearance: 12m
6	Close Formation Flight with Pilot Adjustments	Varying Clearance: Forward 24±12m, Lateral ±12m, Vertical ±12m
7	Formation Flight, Holding Pattern	Forward Clearance: 12m Vertical Clearance: -2m (corrective bias)
8	Formation Flight, Holding Pattern	Forward Clearance: 12m Vertical Clearance: -2m (corrective bias)
9	Close Formation Flight with Pilot Adjustments	Varying Clearance: Forward 24±12m, Lateral ±12m, Vertical -2m
10	Formation Flight, Holding Pattern	Forward Clearance: 12m Vertical Clearance: -2m (corrective bias)

Flight Experiments

Steady State Performance Analysis: Straight Legs

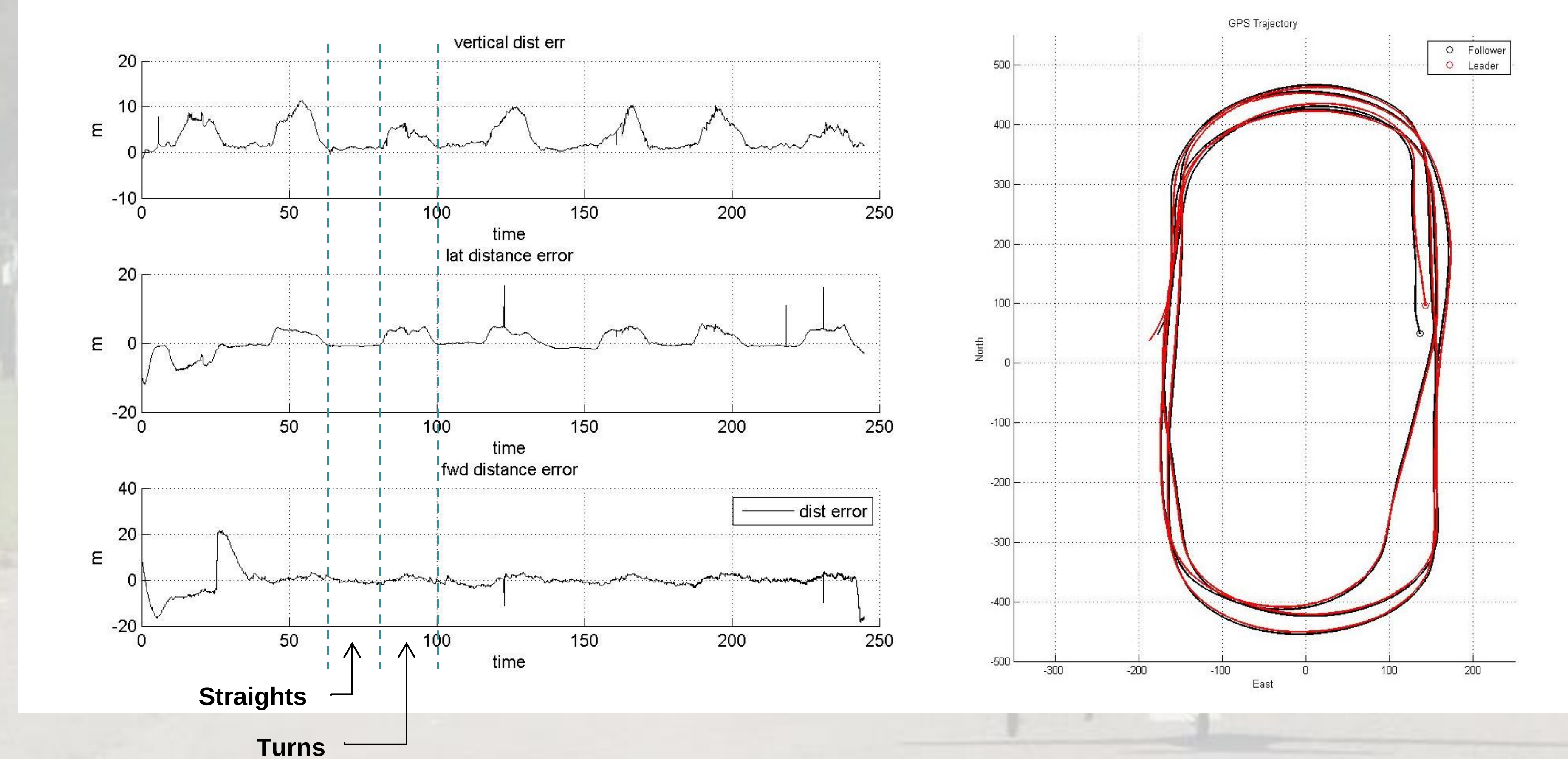
FF Straight legs		Clearance	Max Err. Distance	Mean Abs. Err. Distance	Mean Err. Distance	Std. Dev.	avg. % wing span
Flight 1	Forward (m)	50	-6.112	2.623	-2.356	1.896	98%
	Lateral (m)	0	-5.615	2.011	-1.628	1.985	68%
	Vertical (m)	0	4.778	2.617	2.617	0.993	109%
	Magnitude (m)	50	9.577	4.216	3.879	2.919	162%
Flight 2	Forward (m)	40	-3.700	2.144	-2.144	0.539	89%
	Lateral (m)	0	-8.447	2.803	-2.640	1.890	110%
	Vertical (m)	0	5.973	2.730	2.730	1.333	114%
	Magnitude (m)	40	10.987	4.461	4.361	2.374	182%
Flight 3	Forward (m)	30	-2.281	0.798	-0.744	0.552	31%
	Lateral (m)	0	-5.496	1.725	-1.381	1.380	58%
	Vertical (m)	0	6.322	2.357	2.357	1.041	98%
	Magnitude (m)	30	8.681	3.027	2.831	1.815	118%
Flight 5	Forward (m)	12	2.068	0.533	0.494	0.486	21%
	Lateral (m)	0	-1.890	1.193	-1.050	0.695	44%
	Vertical (m)	0	3.088	2.391	2.391	0.386	100%
	Magnitude (m)	12	4.170	2.724	2.657	0.931	111%
Flight 7	Forward (m)	12	1.899	0.649	-0.499	0.596	21%
	Lateral (m)	1.2	0.551	0.184	-0.021	0.238	1%
	Vertical (m)	2	2.229	1.640	1.640	0.212	68%
	Magnitude (m)	12.2	2.979	1.773	1.715	0.676	71%
Flight 8	Forward (m)	12	1.529	0.536	-0.143	0.596	6%
	Lateral (m)	1.2	1.083	0.606	-0.606	0.225	25%
	Vertical (m)	2	2.027	1.302	1.302	0.327	54%
	Magnitude (m)	12.2	2.760	1.533	1.443	0.716	60%
Flight 10	Forward (m)	12	3.563	1.763	-1.521	1.239	63%
	Lateral (m)	1.2	0.386	0.129	-0.023	0.157	1%
	Vertical (m)	2	2.350	1.696	1.696	0.368	71%
	Magnitude (m)	12.2	4.286	2.450	2.278	1.301	95%

***Flights 4,6, and 9 are not analyzed because the formation geometry was varying during the flights.**
**** GPS error was not considered in the performance analysis.**

Steady State Performance Analysis: Turns

FF Turns		Clearance	Max Err. Distance	Mean Abs. Err. Distance	Mean Err. Distance	Std. Dev.	avg. % wing span
Flight 1	Forward (m)	12	-12.475	5.650	-7.177	5.220	299%
	Lateral (m)	0	-22.371	8.048	-12.949	5.437	540%
	Vertical (m)	0	9.051	4.209	5.481	2.247	228%
	Magnitude (m)	12	27.166	10.696	15.786	7.865	658%
Flight 2	Forward (m)	12	-5.968	3.300	-4.788	0.641	200%
	Lateral (m)	0	-11.773	5.251	-8.406	1.606	350%
	Vertical (m)	0	7.942	3.327	4.091	1.805	170%
	Magnitude (m)	12	15.405	7.038	10.503	2.500	438%
Flight 3	Forward (m)	12	-5.010	1.713	-2.940	0.649	123%
	Lateral (m)	0	-7.350	3.211	-5.198	1.865	217%
	Vertical (m)	0	12.051	4.107	6.452	2.673	269%
	Magnitude (m)	12	14.978	5.487	8.792	3.324	366%
Flight 5	Forward (m)	12	1.986	0.762	0.729	0.445	30%
	Lateral (m)	0	3.438	2.394	2.394	0.524	100%
	Vertical (m)	0	9.485	3.960	3.960	1.052	165%
	Magnitude (m)	12	10.282	4.690	4.684	1.256	195%
Flight 7	Forward (m)	12	2.951	1.863	1.863	0.445	78%
	Lateral (m)	1.2	4.177	3.180	3.180	0.469	132%
	Vertical (m)	2	6.812	4.265	4.265	1.380	178%
	Magnitude (m)	12.2	8.518	5.637	5.637	1.524	235%
Flight 8	Forward (m)	12	6.059	3.431	3.431	1.307	143%
	Lateral (m)	1.2	4.402	3.836	3.836	0.221	160%
	Vertical (m)	2	8.423	5.994	5.994	1.015	250%
	Magnitude (m)	12.2	11.271	7.900	7.900	1.669	329%
Flight 10	Forward (m)	12	3.338	0.949	0.818	0.885	34%
	Lateral (m)	1.2	4.512	3.561	3.561	0.479	148%
	Vertical (m)	2	11.391	8.718	8.718	1.585	363%
	Magnitude (m)	12.2	12.699	9.465	9.452	1.877	394%

Sample Flight Data



Outline

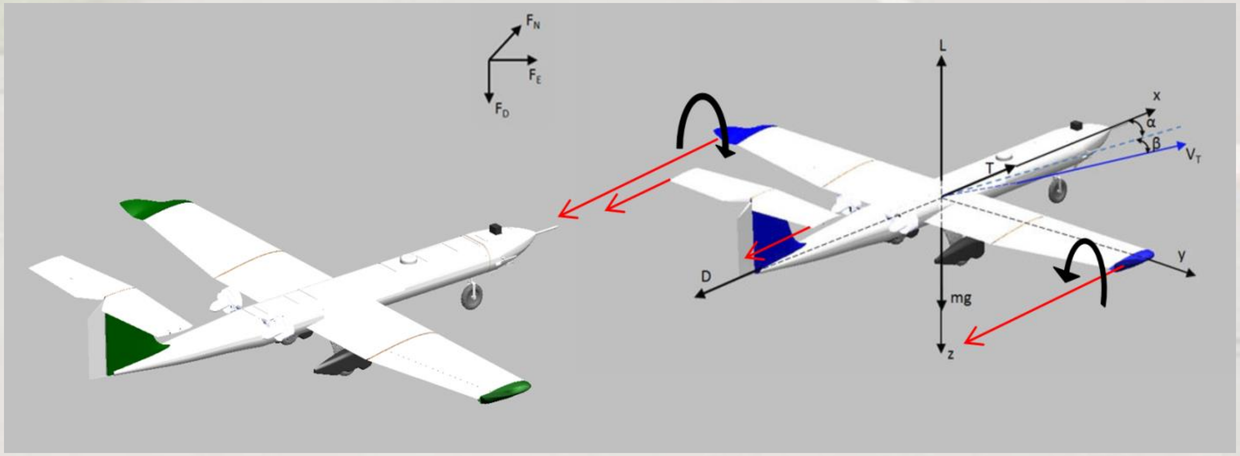
Cooperative Wind/Wake Estimation in Formation Flight

Basic Strategy

- Leader: measurement of local wind field,
- Follower: measurement of local wind field + wake generated by the leader.

Outline

- 3D wind estimation using Unscented Kalman Filter (UKF).
- Cooperative estimation of wind field using UKF.
- Wake sensing in UAV formation flight (flight test results).



Wind Estimation Using Unscented Kalman Filter

Kinematic Equations for UKF Approach

- UKF was selected over EKF because of its effective linearization technique and ease of implementation.
- Update equation: $x = [U, V, W, \Phi, \theta, \psi, w_x, w_y, w_z]$:

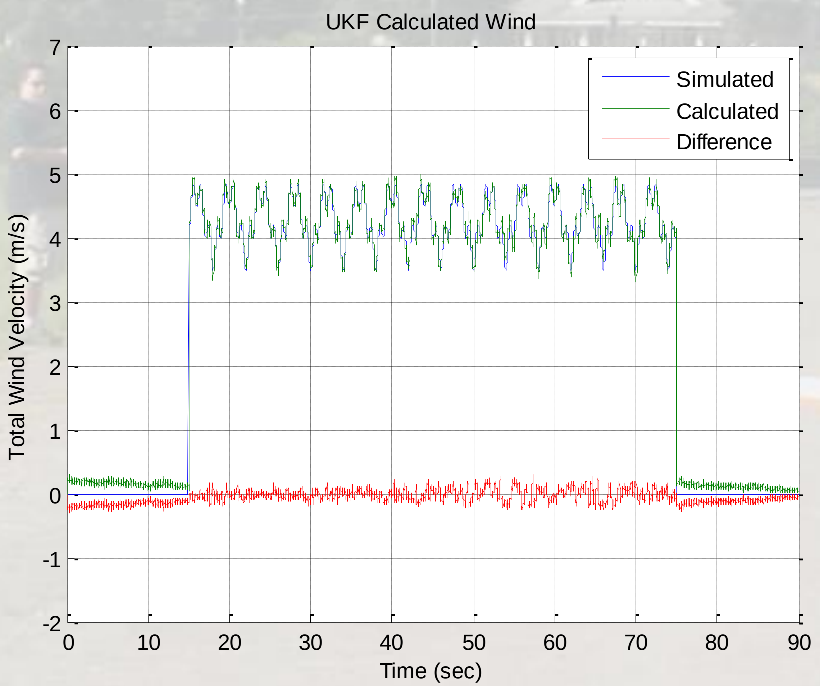
$$\begin{bmatrix} \dot{U} \\ \dot{V} \\ \dot{W} \end{bmatrix} = \begin{bmatrix} rV - qW + a_x \\ pW - rU + a_y \\ qU - pV + a_z \end{bmatrix} + DCM(\Phi, \theta, \psi)^T \begin{bmatrix} 0 \\ 0 \\ g \end{bmatrix}$$

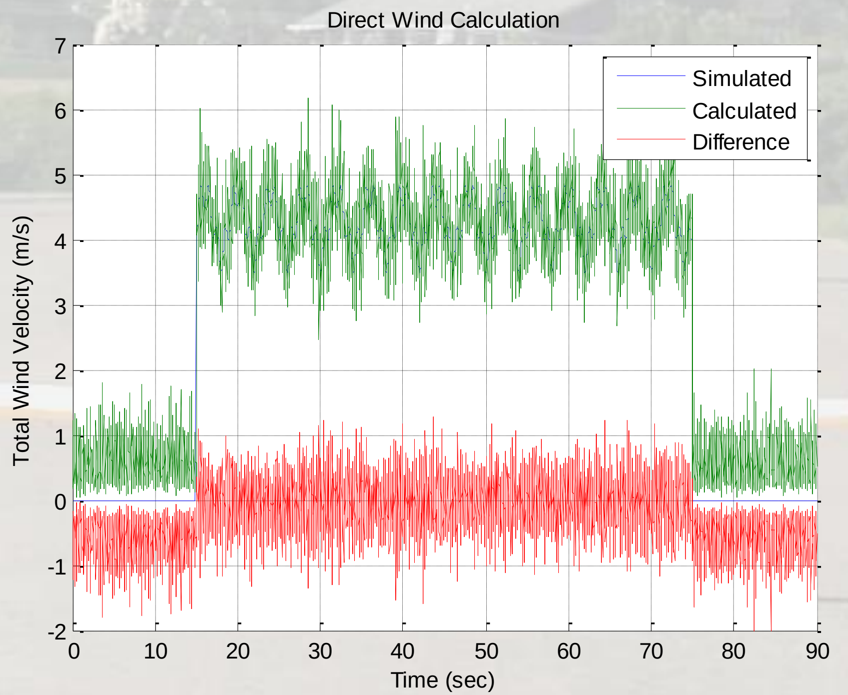
- Measurement equation:

$$\begin{bmatrix} V_{pitot} \\ \alpha \\ \beta \end{bmatrix} = \begin{bmatrix} U \\ tan^{-1}(\frac{W}{U}) \\ sin^{-1}(\frac{V}{U^2+V^2+W^2}) \end{bmatrix}, \quad \begin{bmatrix} V_x \\ V_y \\ V_z \end{bmatrix} = DCM(\Phi, \theta, \psi) \begin{bmatrix} U \\ V \\ W \end{bmatrix} + \begin{bmatrix} w_x \\ w_y \\ w_z \end{bmatrix}$$

Wind Estimation Using Unscented Kalman Filter

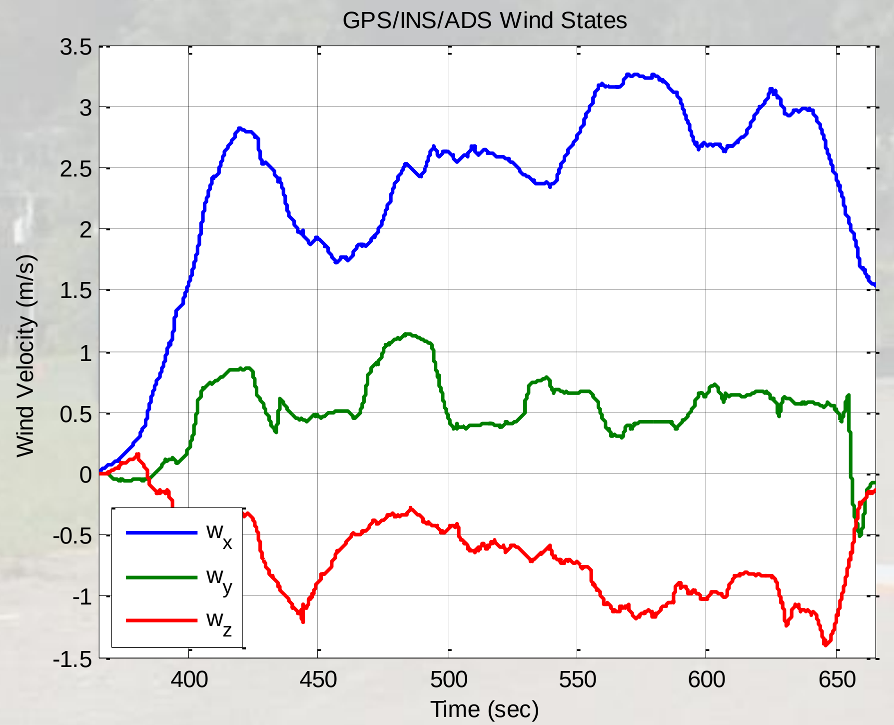
- Simulator sensor noise from "Phastball" UAV GPS/INS/ADS
- Compared results with a direct calculation method
  - » UKF mean: -0.0676 deg., std: 0.0836
  - » Direct mean: -0.2058 deg. , std: 0.4233



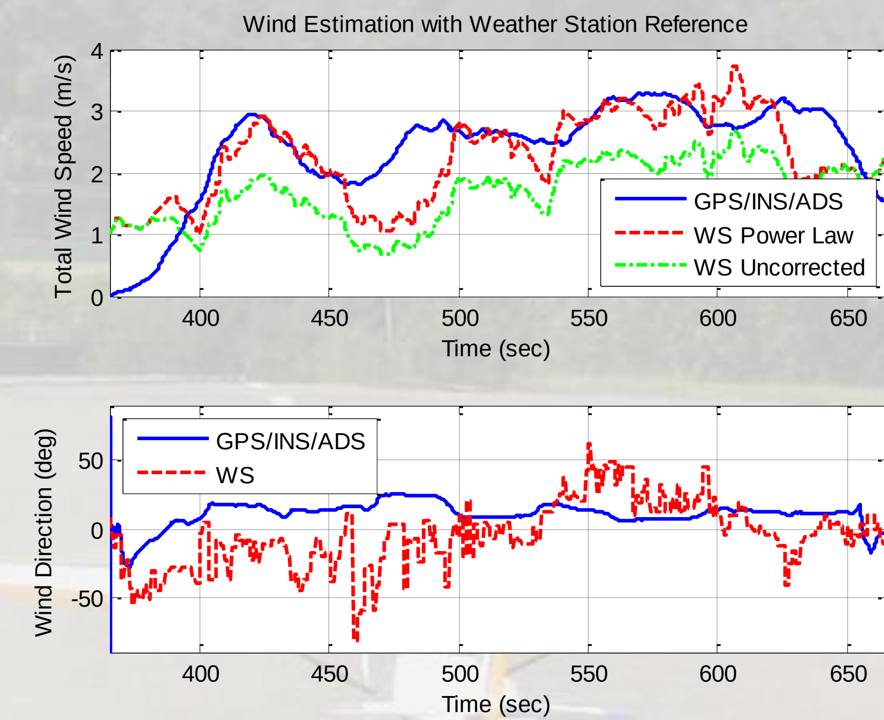


Wind Estimation Using Unscented Kalman Filter

- Validation using flight test data and ground weather station



UKF estimation of 3D wind.



Horizontal planar wind speed and direction.

Cooperative Gust Sensing with UAV Formations: Simulation Results

- UKF1 is to estimate the 3D wind field using only the local measurements. Leader/follower wind estimation can be obtained separately using UKF1.
- UKF2 is a cooperative strategy to estimate the local wind field using both leader and follower information. Wake predictions from the leader are added to the measurement equations of UKF2.
- “1 minus cosine” gust profile and Phastball wake model is used in simulation.

		Leader Wind Estimation (UKF1)	Follower Wind Estimation (UKF1)	Cooperative Wind Estimation (UKF2)
Mean of error	x (m./s.)	0.5138	0.4568	0.5500
	y (m./s.)	1.1869	1.4173	1.1595
	z (m./s.)	0.2518	0.2564	0.2280
Norm	(m./s.)	1.3176	1.5111	1.3034
Std. of error	x (m./s.)	0.3254	0.3256	0.3428
	y (m./s.)	0.8071	0.8761	0.8216
	z (m./s.)	0.2263	0.2557	0.2270
Norm	(m./s.)	0.8991	0.9690	0.9187

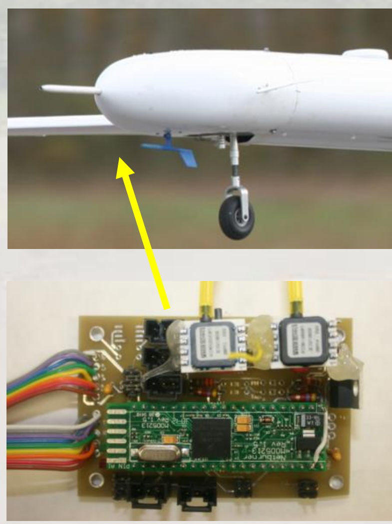
Gust Suppression with UAV Formations

- **Motivations**
  - How to utilize the wind information measured by the leader?
  - How to compensate for the vortex turbulence during tight formation flight?
- **On-Going Efforts**
  - Longitudinal dynamics is focused for the proof of the concept.
  - A feed forward controller is being added to the current inner loop flight controller using the developed gust/wake estimation.
  - Initial work will be on the validation of the concept without the wake effect.
  - Given the estimated wake location and strength, how to design a new controller for gust suppression control.

Wake Sensing: Flight Results

- Nose board provides:
  - Static/dynamic pressure data from Pitot tube,
  - Flow angles from two alpha vanes and one beta vane.
- Weather station collects wind speed and direction data on the ground.
- The air data system was calibrated on a calm day.

Flow angle potentiometers

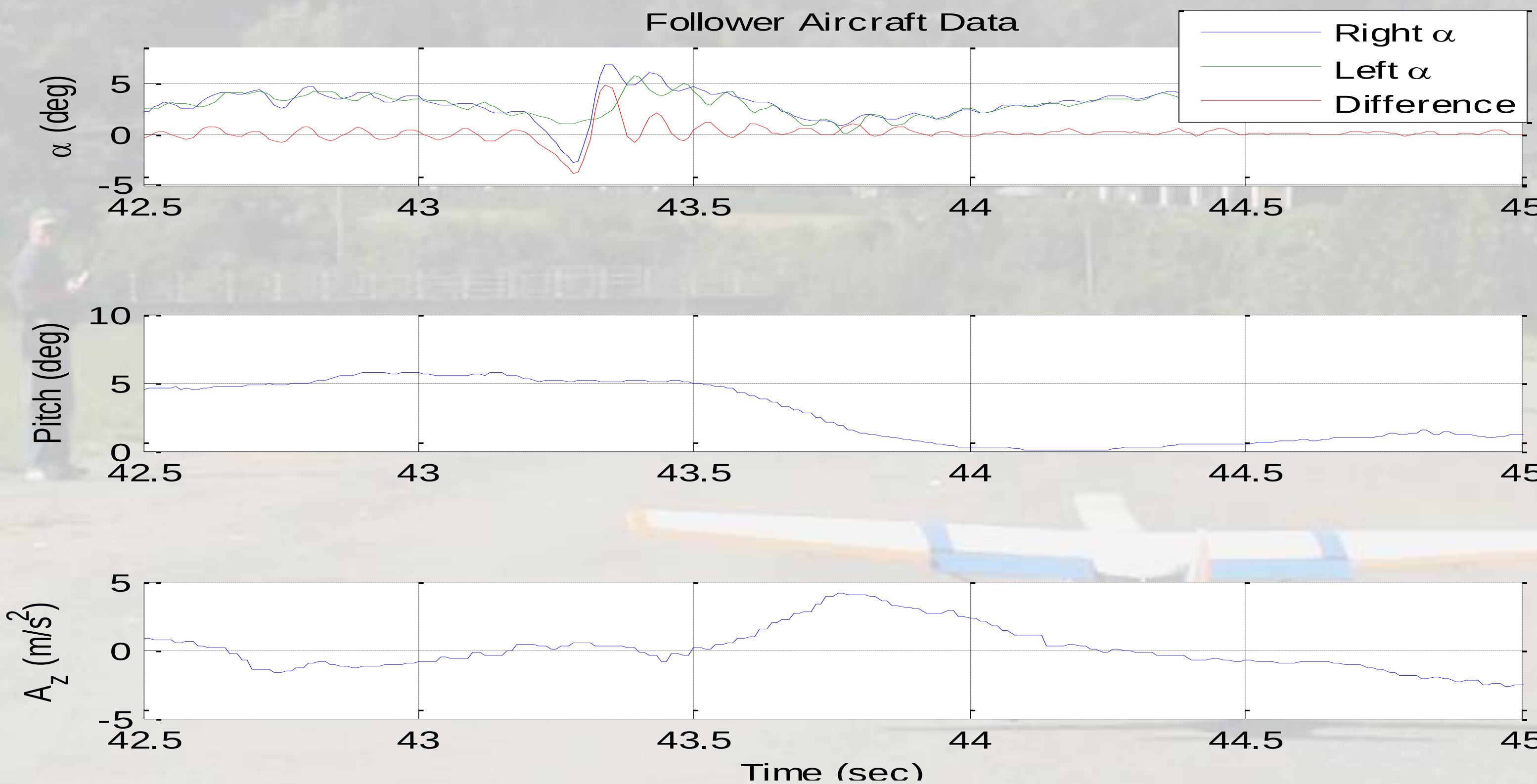


Pressure sensor board

Ground Weather Station

Wake Sensing: Flight Results (Cont.)

- Wake experienced by the Follower (the left and right α vanes are 25 cm. apart laterally)



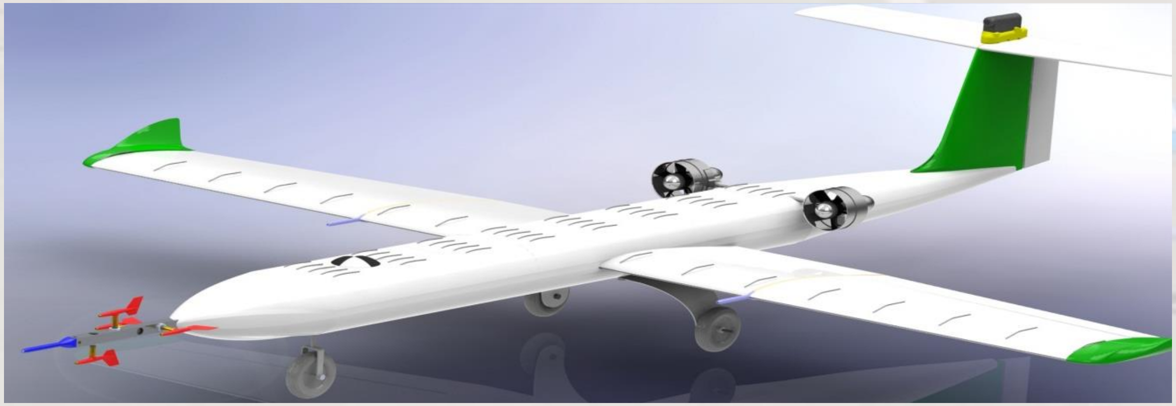
Outline

Conclusions

- Successfully achieved close formation flight (up to 5 *b* or ~12 m.) with 2 low-cost UAV research platforms. The developed formation flight controller behaved desirably within ~1 m. standard deviation during straight legs.
- Demonstrated that small sub-scale research aircraft (~25 lbs.) can generate vortices strong enough to be sensed by the following aircraft without being buried in the ambient wind turbulences.
- Showed initial advantages for cooperative wind/gust estimation and suppression control with formation flight in simulation.

Plans for Phase II

- “Phastball” platforms to be upgraded with higher quality sensors including RTK GPS (1 cm.) and spatially distributed 5-hole Pitot tubes;
- Investigate the interactions between the ambient wind and wake-induced vortices;
- Real-time estimation of the wake vortex center;
- Real-time cooperative gust sensing and control;
- Quantify the aerodynamic benefits of a dynamic ‘sweet spot’ following close formation flight;
- Scalability analysis for different weight/classes of aircraft.



Thank You!

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